Optical and thermal performance of parabolic trough collectors

Robert Pitz-Paal, Institute of Solar Research

DLR

Overview

1. Motivation for Improving Performance
2. Qualification of Concentrators
3. Qualification of Receivers
4. Conclusions

1. Motivation

Improved Performance by Proper Implementation of Construction

- Solar field has a high share of the total investment
- It is a *long-term* investment
- It is of *big extent* (corrections are expensive)
- Yearly *plant output* strongly depends on optical quality of collector field
    - Measurements showed that without proper quality assurance *3-10%* and in some cases even more of the field performance can be lost
- *Quality assurance* and *final acceptance tests* of collector fields are necessary for control of subcontractors and warranty claims

➔ **Quality assurance of collector field assembly is indispensable and makes economic sense**

What is a parabolic trough?

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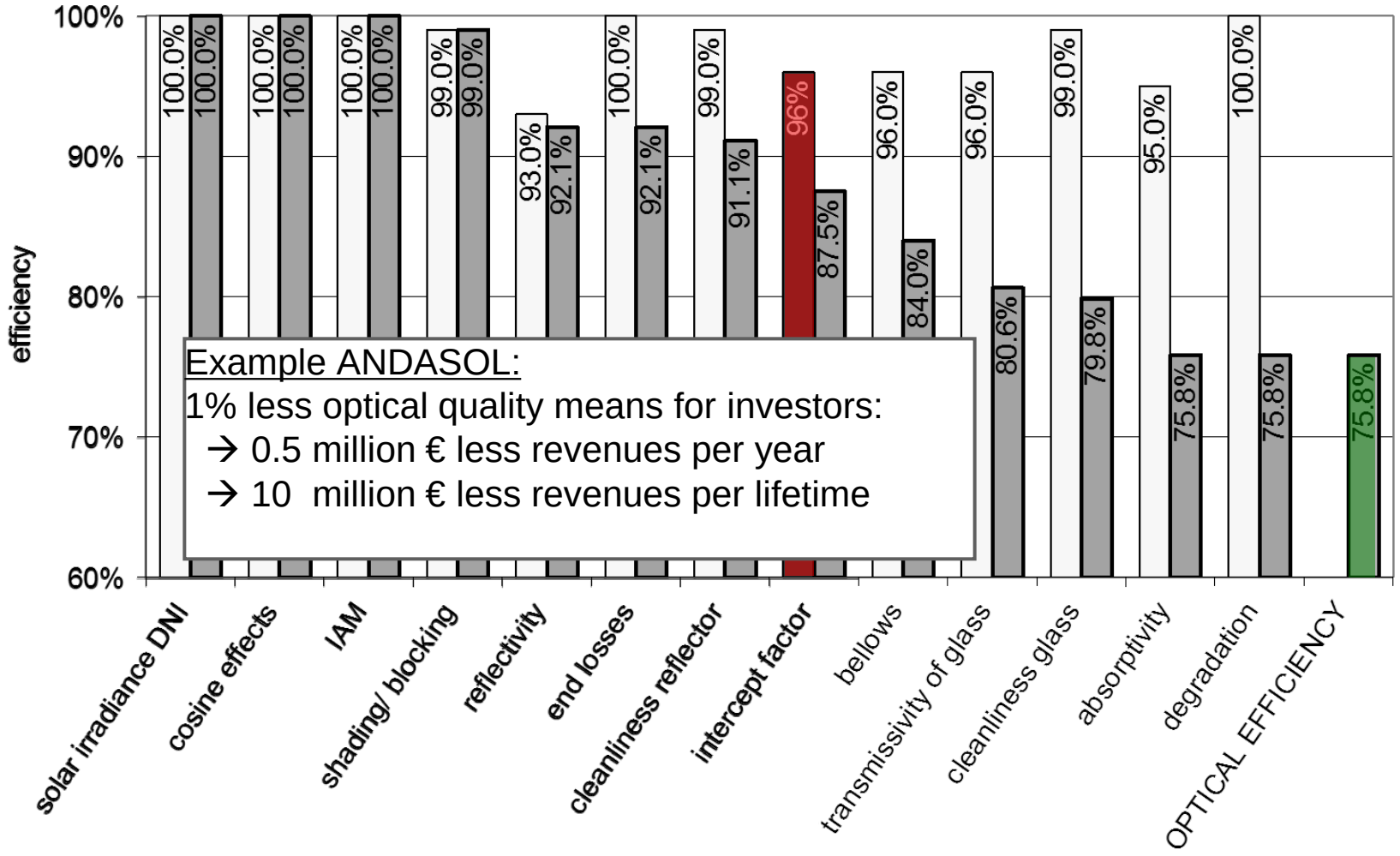
1. Motivation

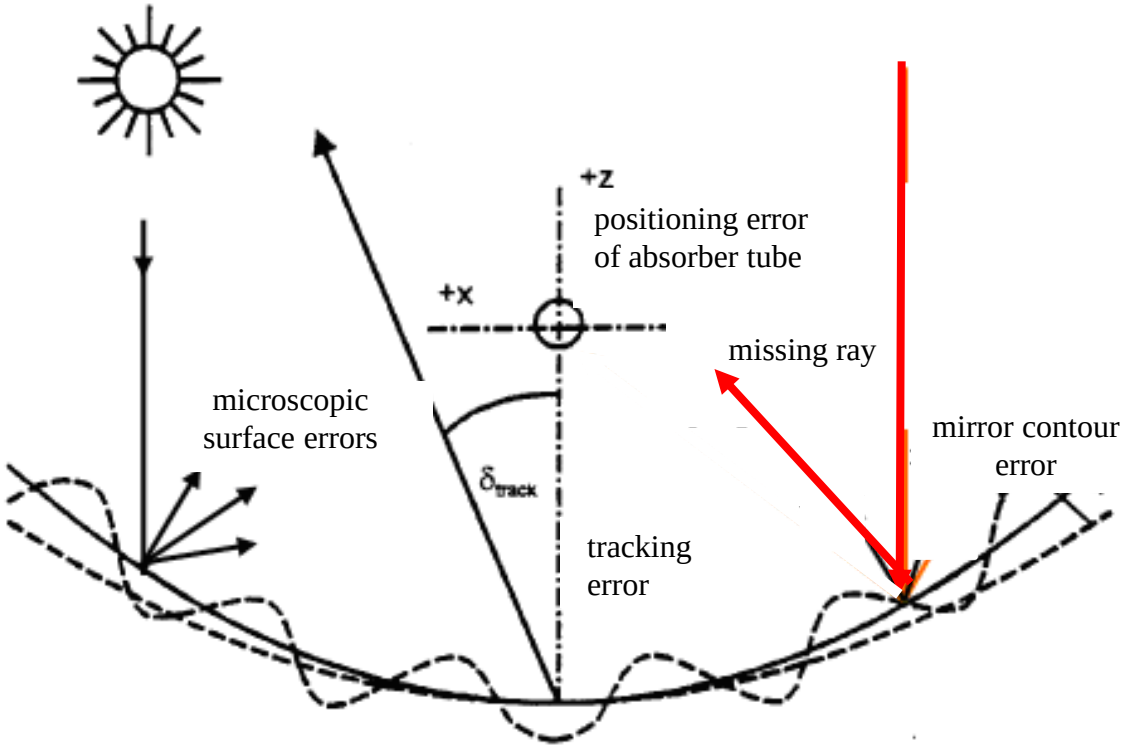
Efficiency Chain, Example: Parabolic Trough



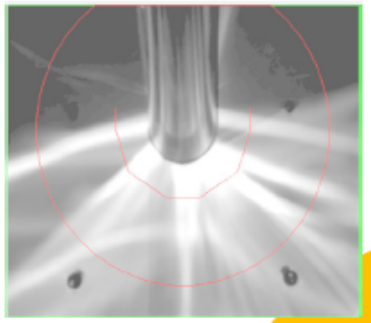
2. Qualification of Concentrators

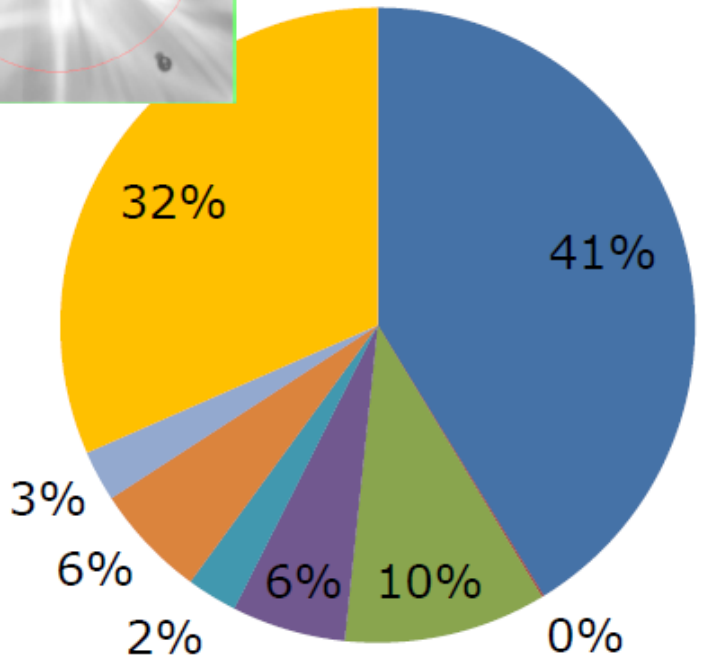
Possible Concentrator Errors

- **Microscopic surface errors** (roughness, deterioration, scratches, …)
- **Macroscopic surface deviations** (waviness, mirror contour errors, deformations, structural errors, …)
- **Positioning of the receiver tube** (position of supports, bending of tube, …)
- **Tracking errors** (tracking, module alignment, collector torsion, …)
- **(Sun Shape)**



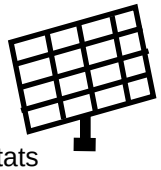
Intercept depends on component quality and alligenement quality





	σ in mrad	$a_i\sigma^2$ in mrad
Mirror Shape*	2	16
Beam Spread	0.2	0.04
Mirror Support*	1	4
Absorber Position	1.5	2.25
Collector Torsion (Loads)	1	1
Module Alignment	1.5	2.25
Tracking Accuracy	1	1
Sun	3.5	12.25
Total	**6.24**	**38.79**
Intercept Factor	**98.7%**	

Qualification in Different Phases

Phases Objects	R&D Phase Prototypes	Production Phase Mass Product	O&M Phase Commissioned Plant
Concentrator  Parabolic Trough Coll.	TARMES Deflectometry + Intercept Simulation Photogrammetry Inclinometer, V-Shot		
 Heliostats			
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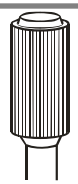
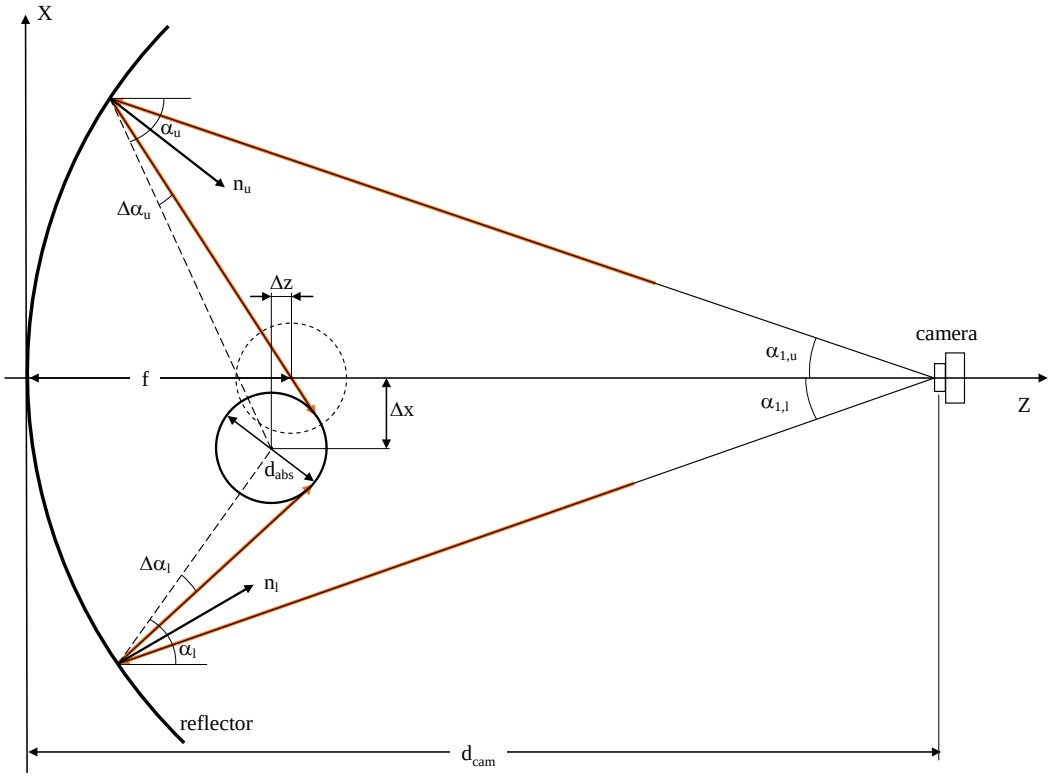
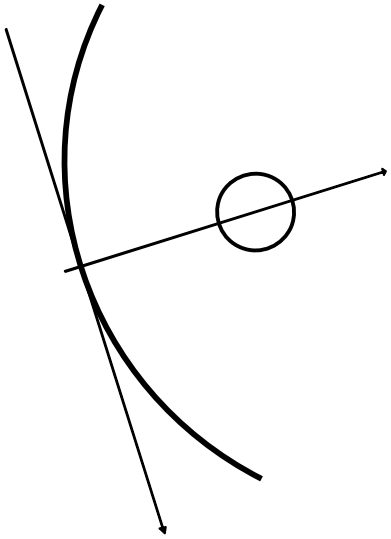
 Central Receiver			

2. Qualification of Concentrators
Deflectometry



2. Qualification of Concentrators

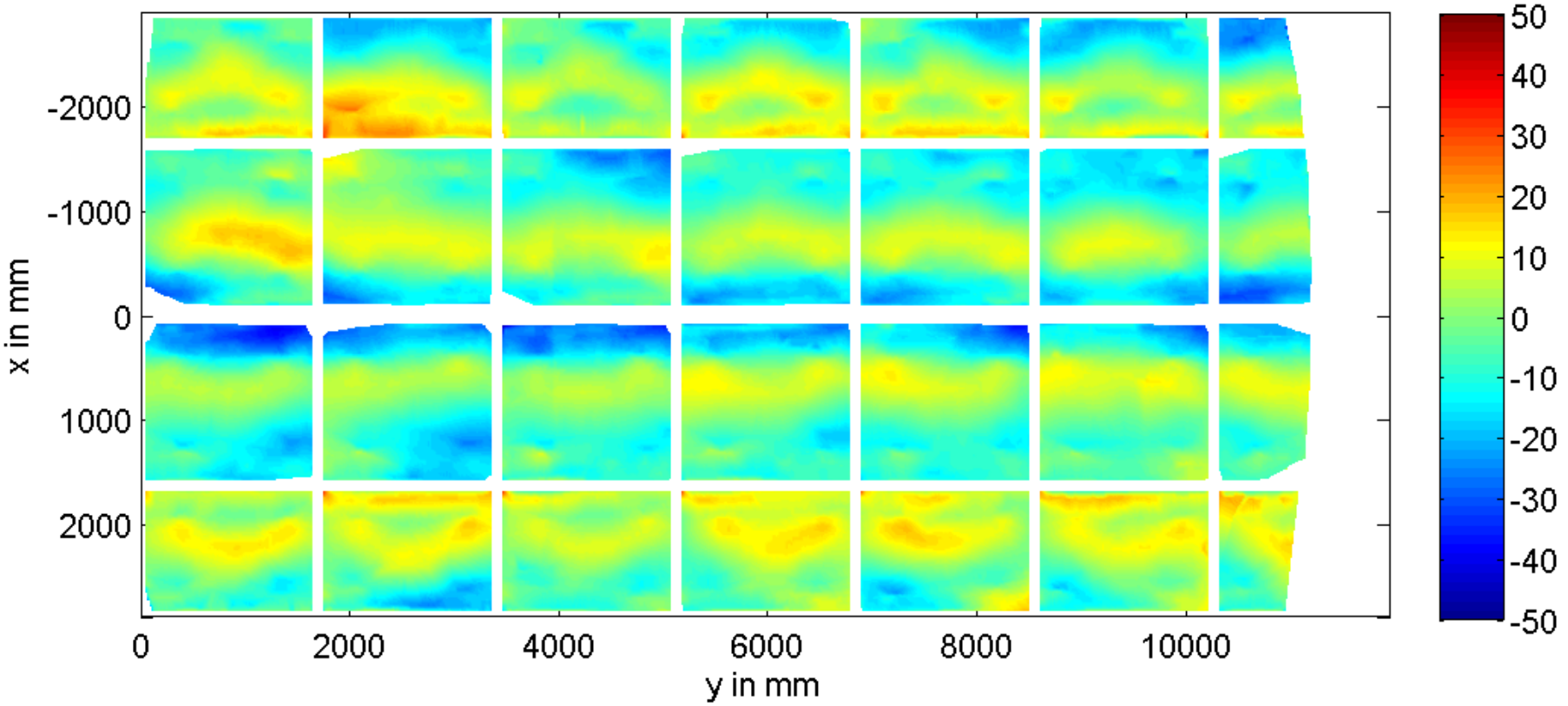
Deflectometry – Image Acquisition



2. Qualification of Concentrators

Deflectometry – Result

Focus deviation in mm of reflected ideal rays

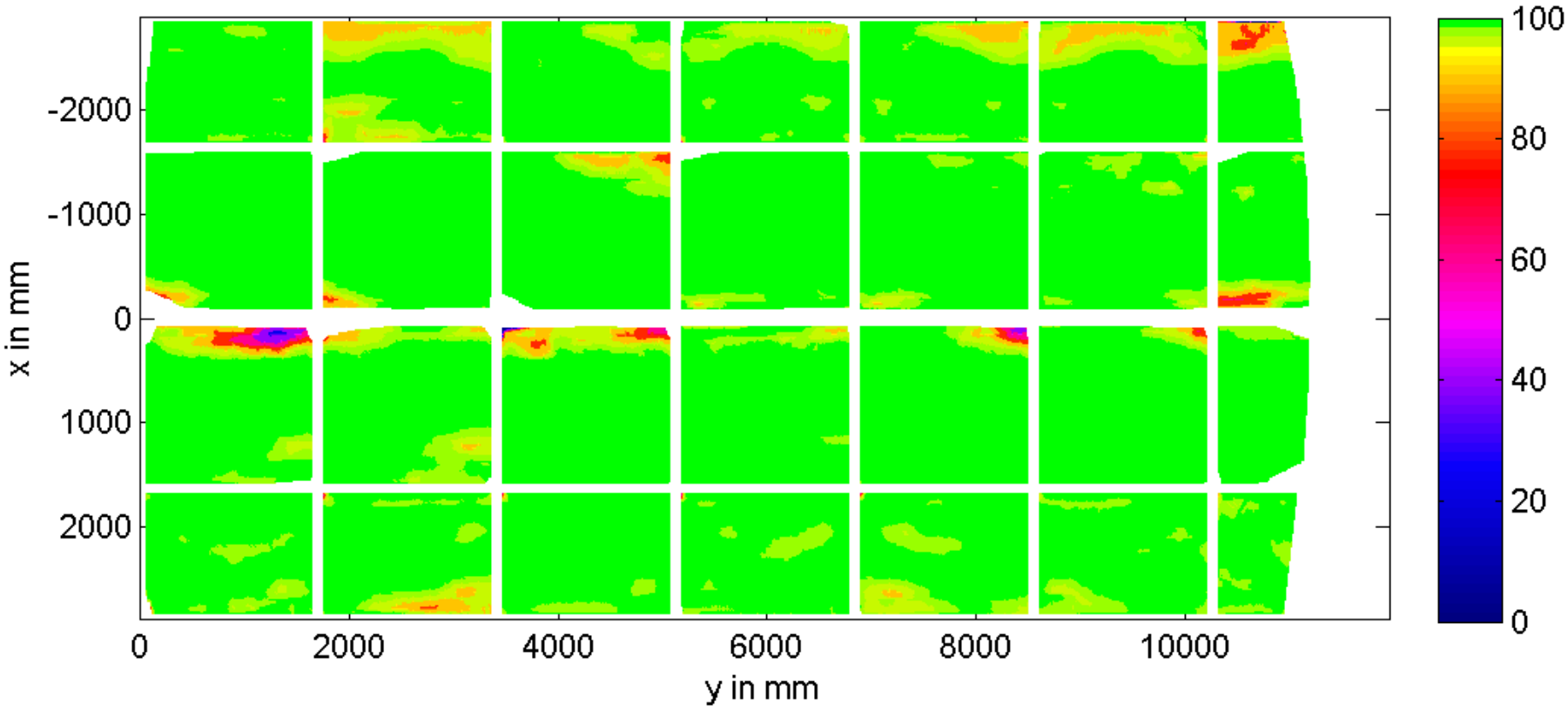


2. Qualification of Concentrators

optical

Deflectometry + Intercept Calculation – Result

Local intercept factor in percent with consideration of degraded sunshape



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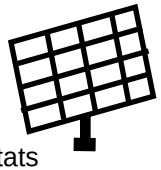 Heliostats			
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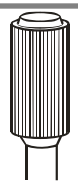
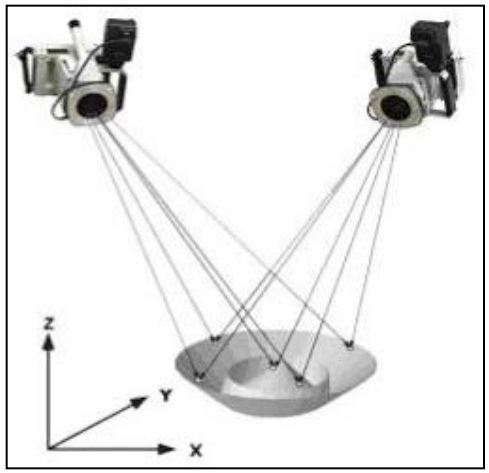
 Central Receiver			
Materials			

2. Qualification of Concentrators

optical

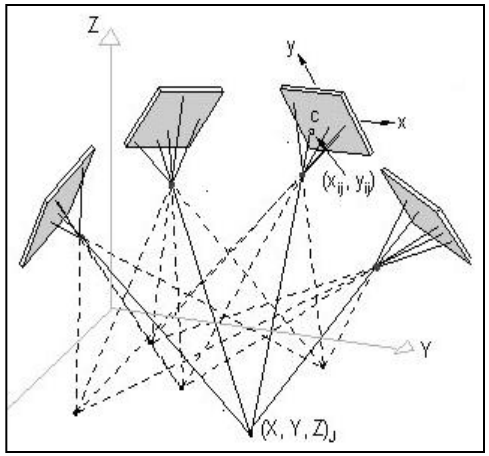
Photogrammetry: Collector Shape and Deformation



From photos to coordinates

- **Image acquisition:** several photos of measurement object are taken form different angles
- **Point recognition:** clearly recognizable points of object are determined in all photos
- **Evaluation:** calculation of 3D point geometry via initial orientation, intersection and bundle adjustment
- **Scaling:** inclusion of known distances between targets

Result: all object coordinates, camera positions and orientations together with their precisions are known

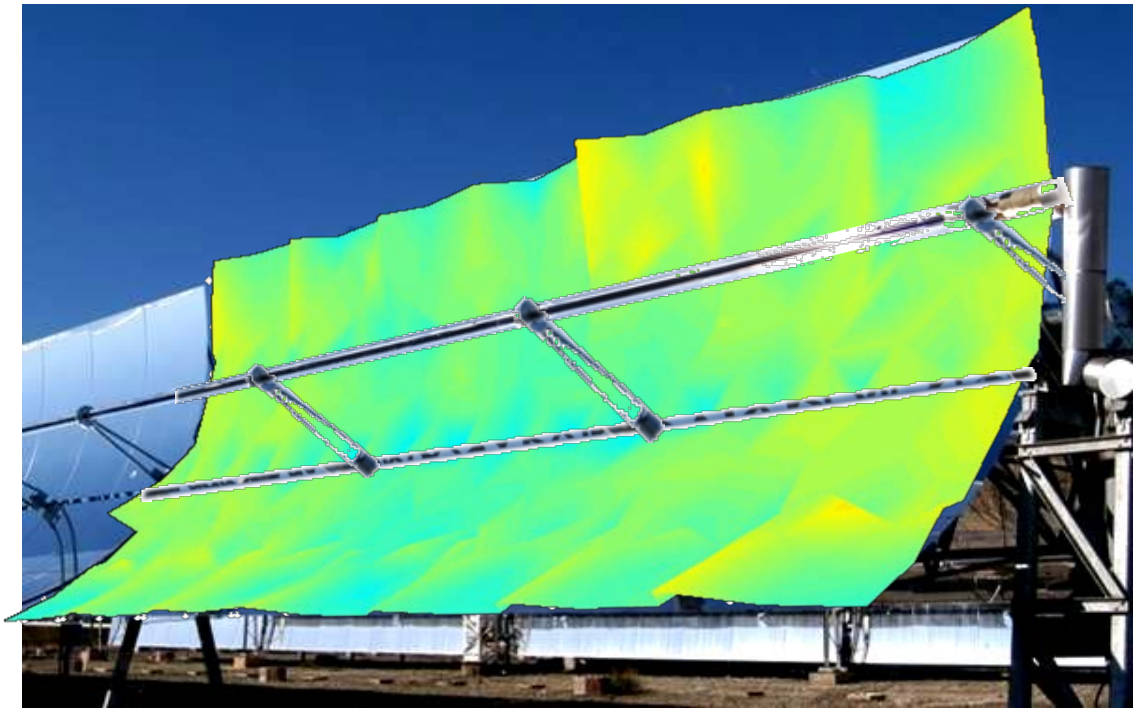


2. Qualification of Concentrators

optical

Photogrammetry: Collector Shape and Deformation

Object Preparation



Results

- 3D Coordinates
  - Coordinate Deviations
  - Angle Deviations
- Shape and Deformation Studies

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Qualification in Different Phases

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	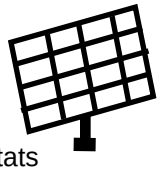 Heliostats	SAPHIR Deflectometry, + Intercept Simulation Photogrammetry, Inclinometer		
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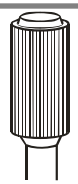
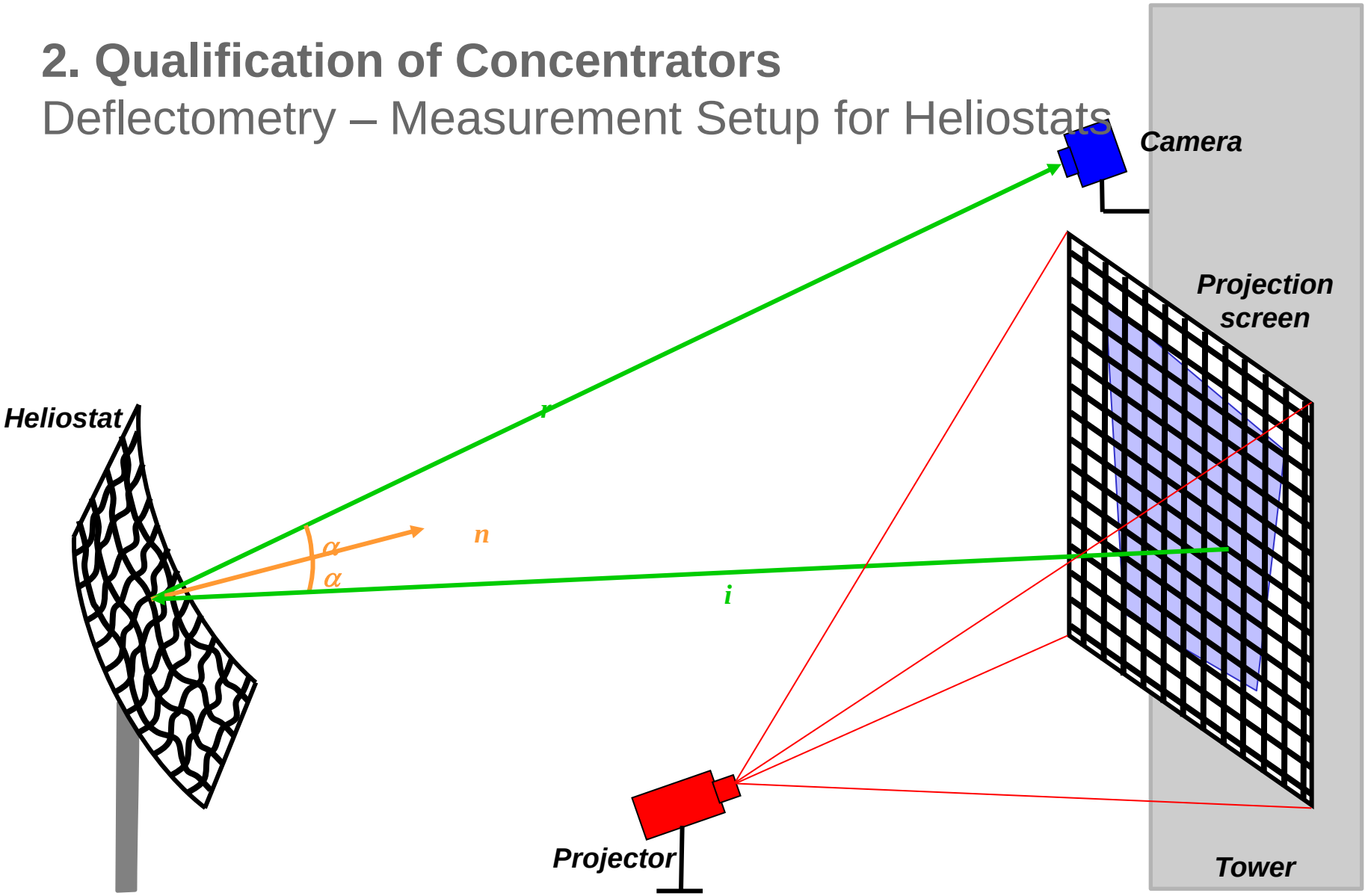
	 Central Receiver			

2. Qualification of Concentrators

Deflectometry – Measurement Setup for Heliostats



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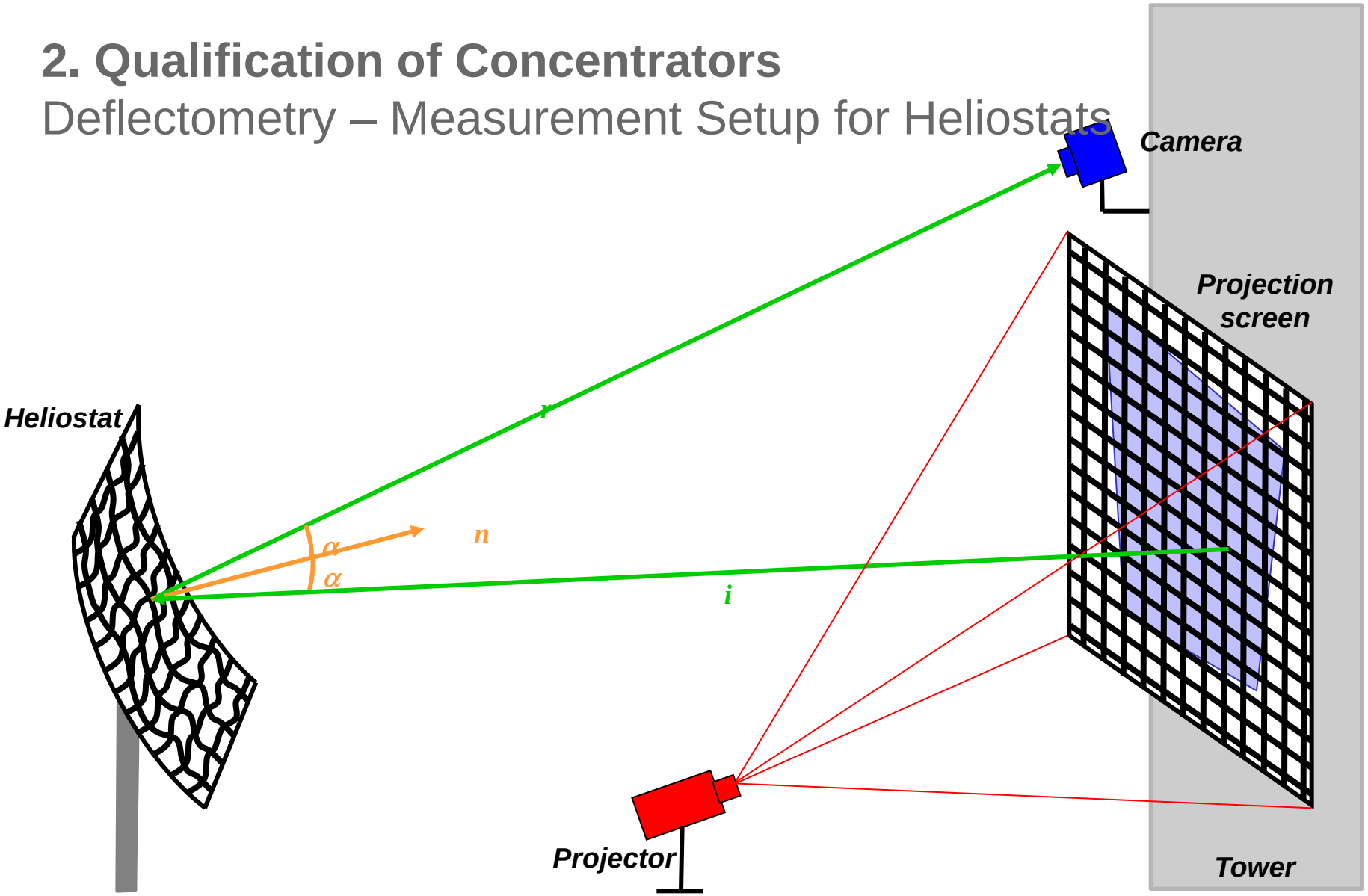
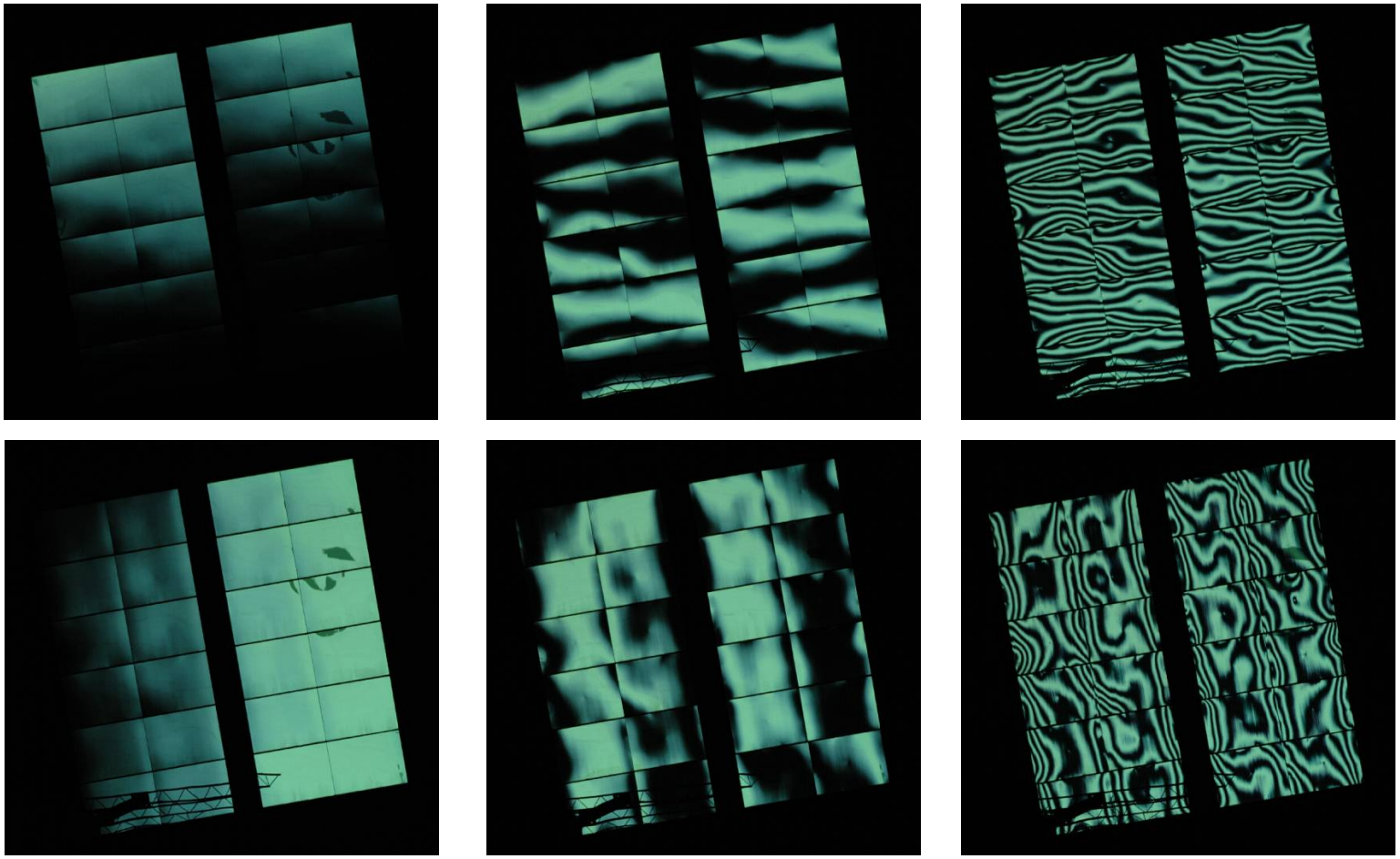


2. Qualification of Concentrators

optical

Deflectometry – Reflected Patterns in Heliostat



horizontal

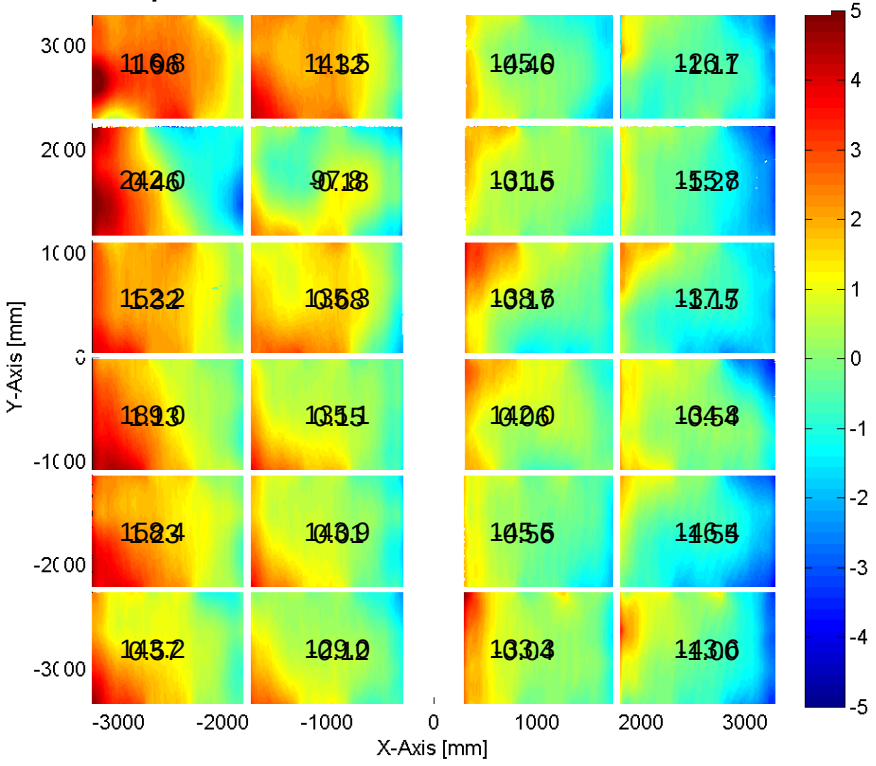
vertikal

2. Qualification of Concentrators

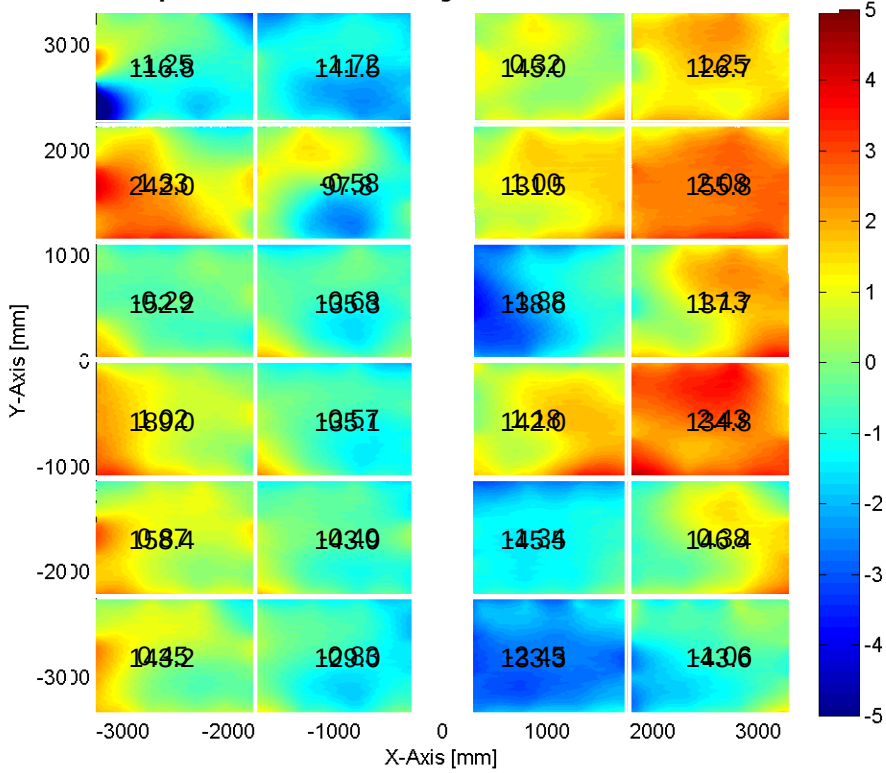
optical

Deflectometry – Results Heliostat CESA-1, PSA

Slope deviation in *x*-direction in mrad



Slope deviation in *y*-direction in mrad



Results on heliostat level:

RMS slope deviation = 1.98 mrad

⇨ adjustments of focal length

Heliostat design focal length = 104.1 m

Measured focal length = 116.2 m

Measured focal length

+ canting

2. Qualification of Concentrators

optical

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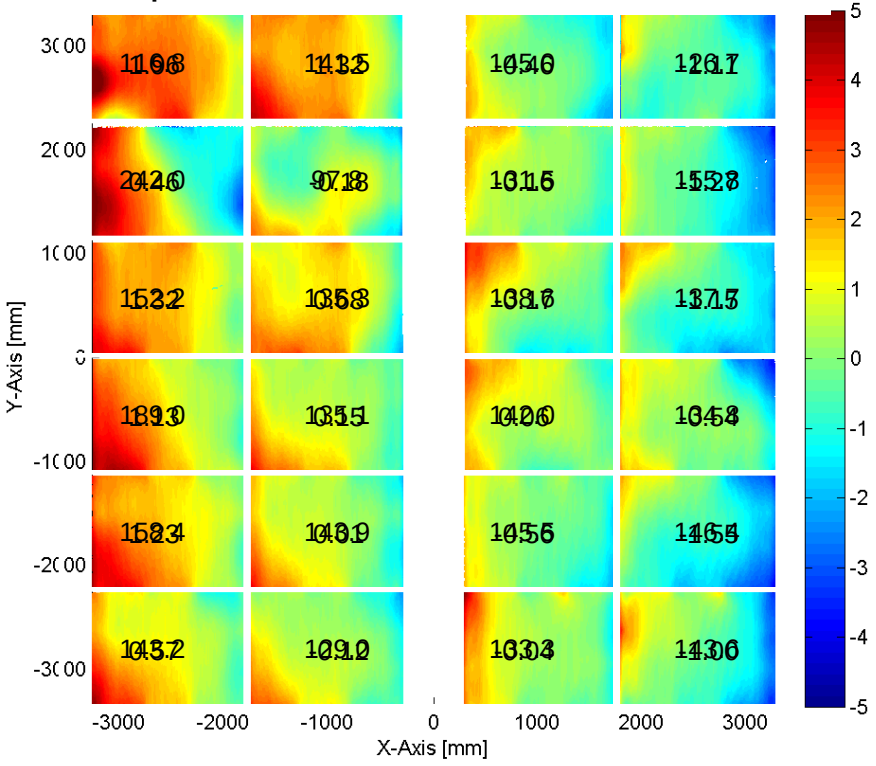

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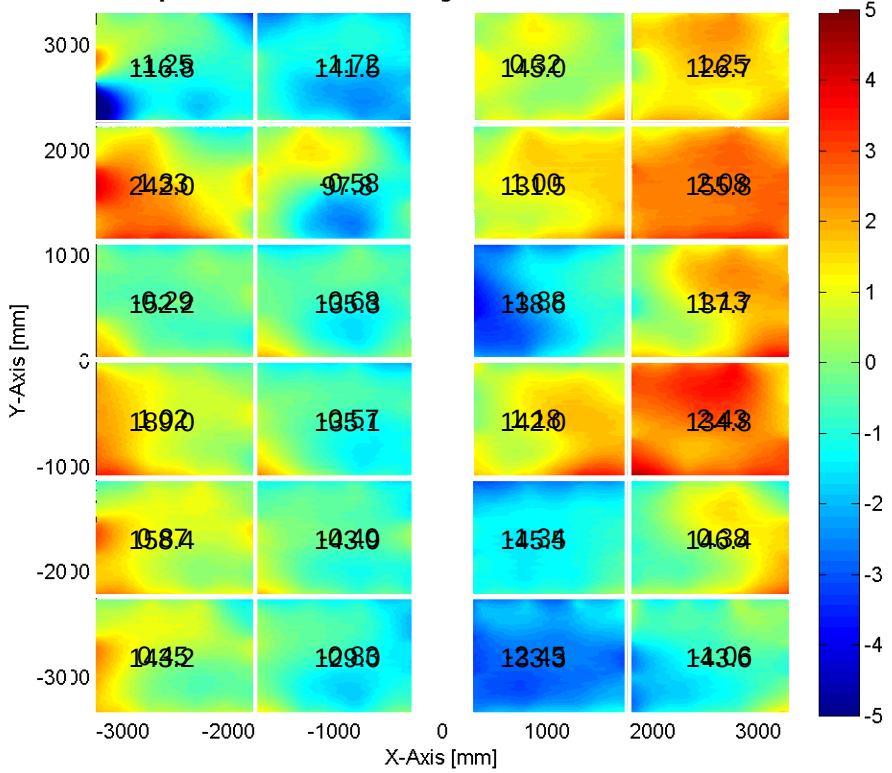

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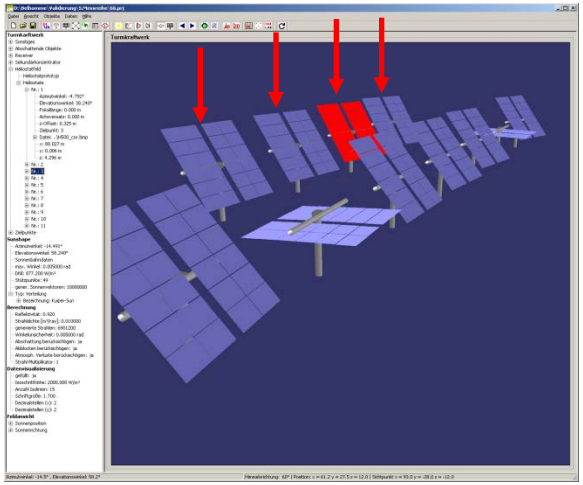
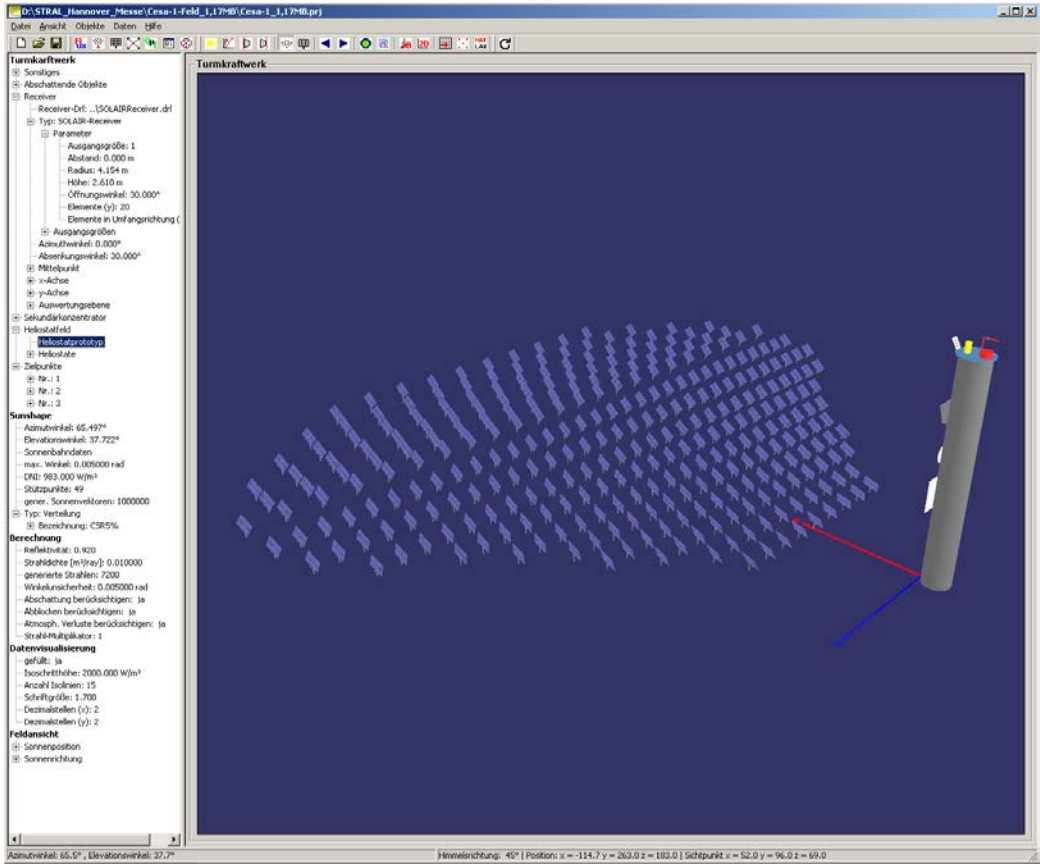
2. Qualification of Concentrators

optical

Deflectometry – Raytracing Heliostats CESA-1, PSA

- STRAL, DLR-Raytracing program which can Use Deflectometry Results
- Code Validation by Simulation of a Group of Heliostats with Blocking and Shading
- Comparison with Flux Measurement



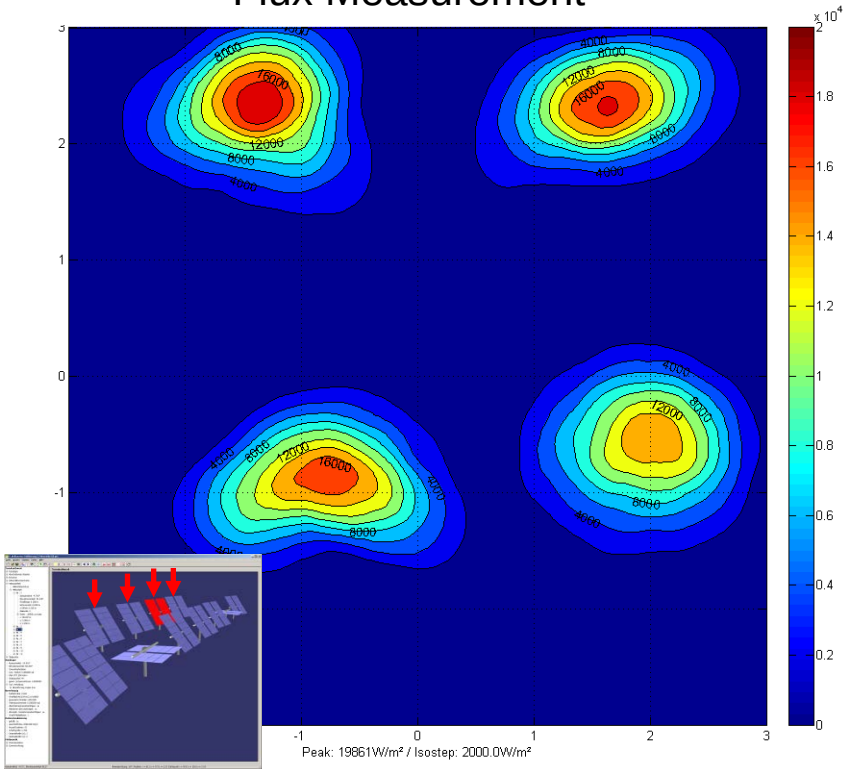


2. Qualification of Concentrators

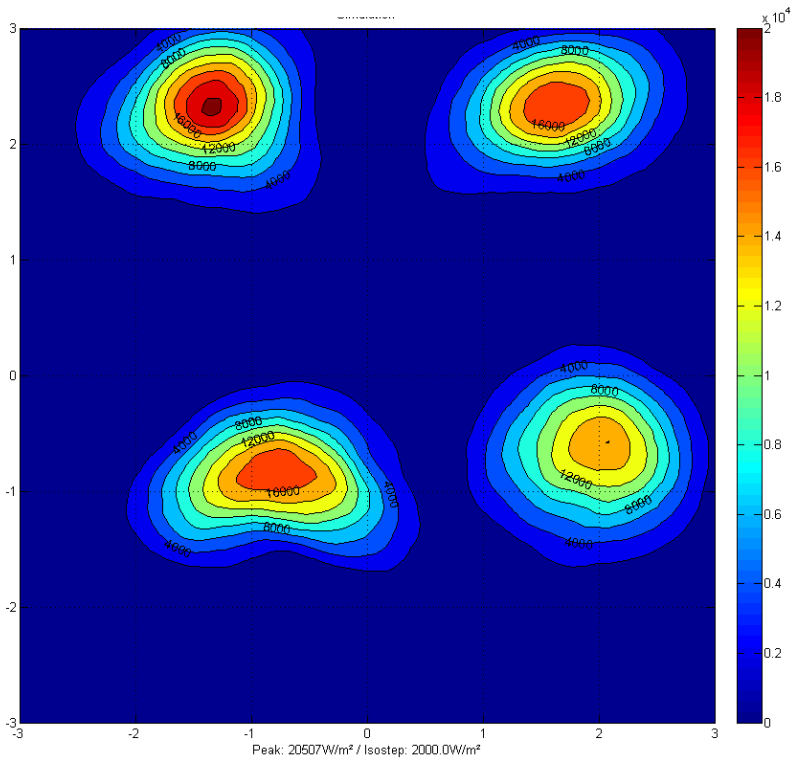
optical

Deflectometry – Raytracing Heliostats CESA-1, PSA

Flux Measurement



Simulation



→ Detailed Simulation of Solar Flux Possible by Using Deflecometry Data

Qualification in Different Phases

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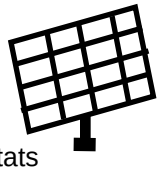 Heliostats	SAPHIR Deflectometry, + Intercept Simulation Photogrammetry, Inclinometer		
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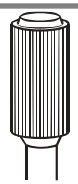
 Central Receiver			

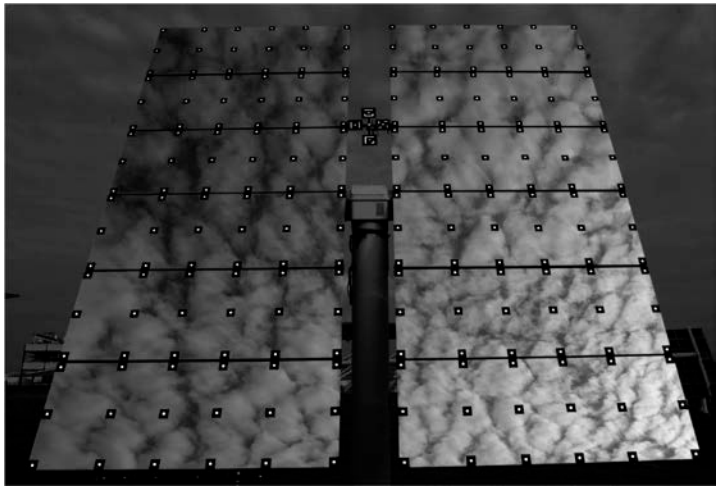
2. Qualification of Concentrators

optical

Photogrammetry: Heliostat Shape and Deformation

Object Preparation

- 216 targets on 12 facets (18 each)



Photogrammetric measurement

- 9 orientations with different elevations (0° ,10° ,20° ,30° ,40° ,50° ,60° ,70° ,80 ° ,90°)
- 20 photos for each orientation

Measurement uncertainty

mean over 9 orientations:

- σ=0.3 mm
- Δ_{max} = 0.6 mm

2. Qualification of Concentrators

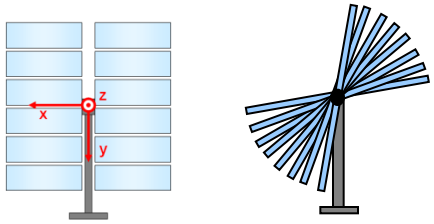
optical

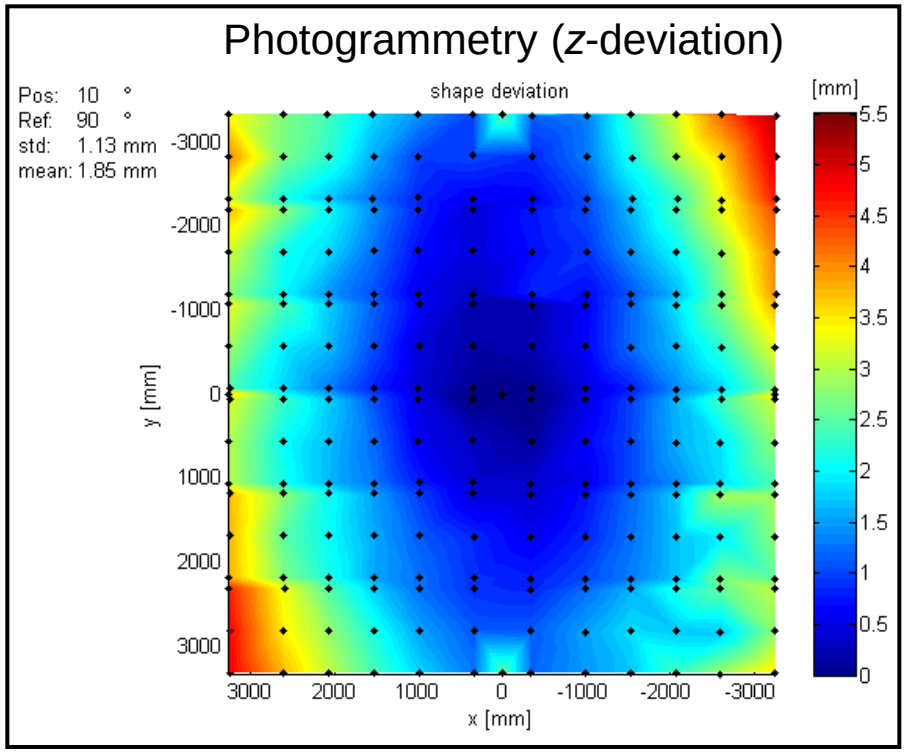
Photogrammetry: Heliostat Shape and Deformation

Measured displacements

Δ between 10° and 90° :

- $\Delta = 1.1 \pm 1.9$ mm
- $\Delta_{max} < 5.5$ mm





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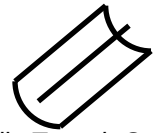
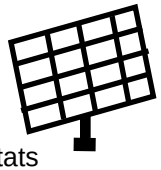
Concentrator  Parabolic Trough Coll.	TARMES Deflectometry + Intercept Simulation Photogrammetry Inclinometer, V-Shot	QDec-M Deflectometry + Intercept Simulation QFoto Photogrammetry, Laser-Tracker	
 Heliostats	SAPHIR Deflectometry, + Intercept Simulation Photogrammetry, Inclinometer		
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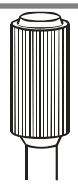
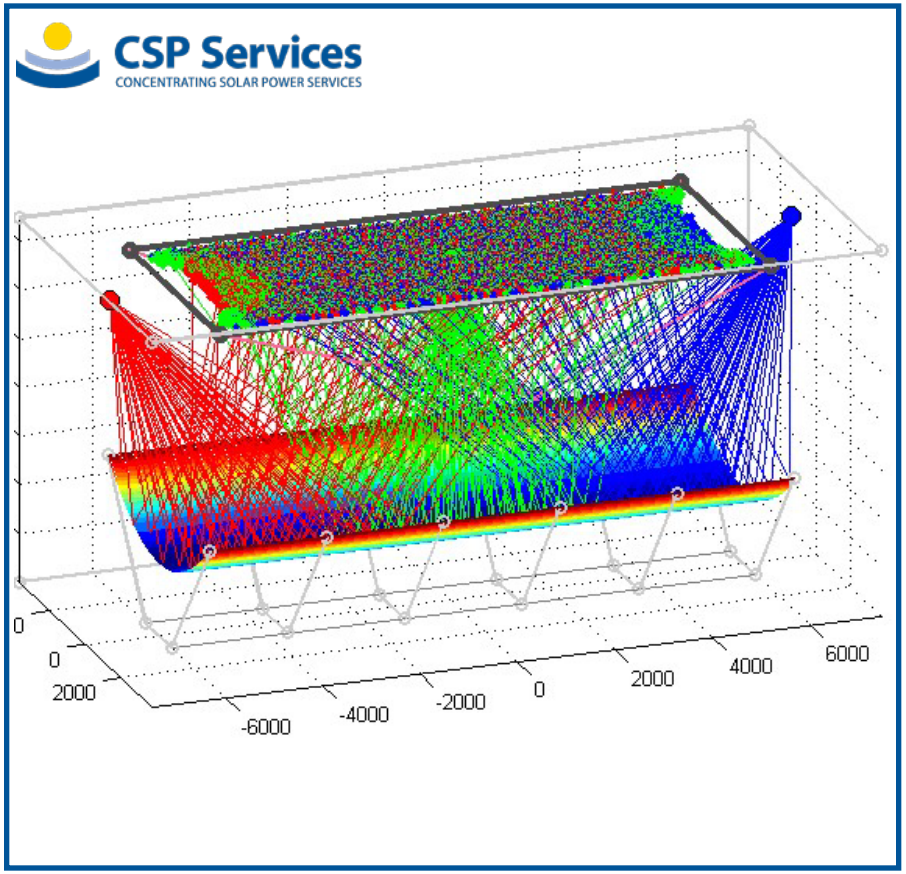
 Central Receiver			

2. Qualification of Concentrators

optical

QDec: Deflectometry Systems for Mirror Panels & Modules



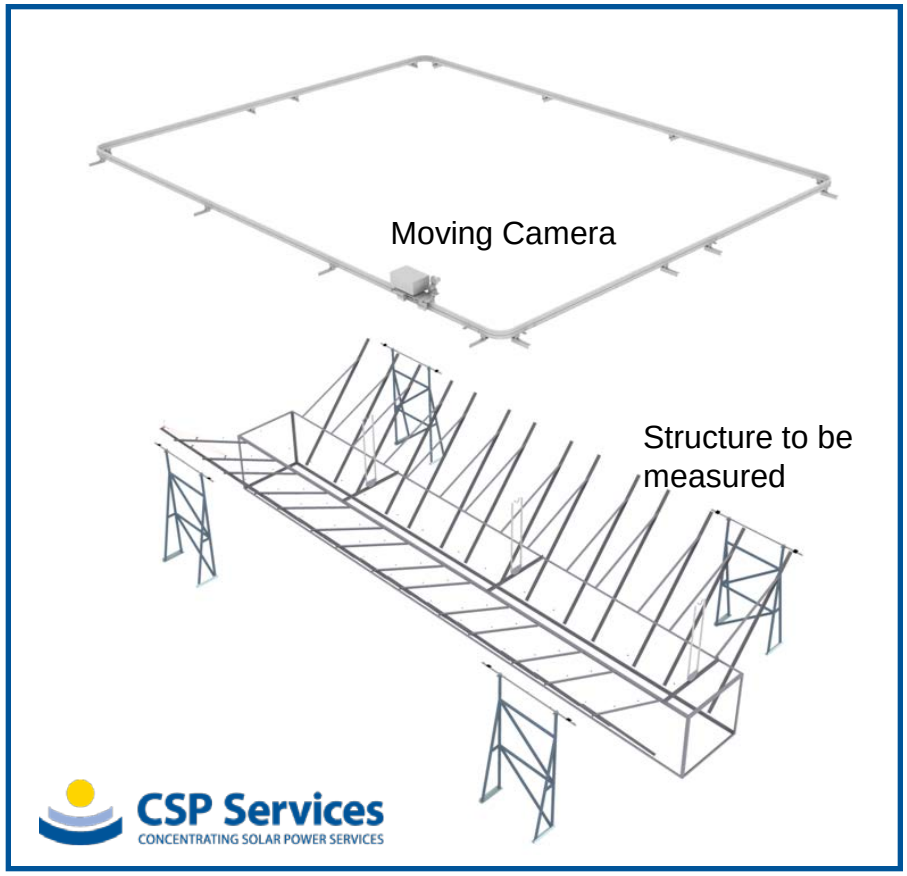
QDec: Automated System for Horizontal and Vertical *Mirror Panels*

QDec-M: Automated System for *12m-Collector Module*

2. Qualification of Concentrators

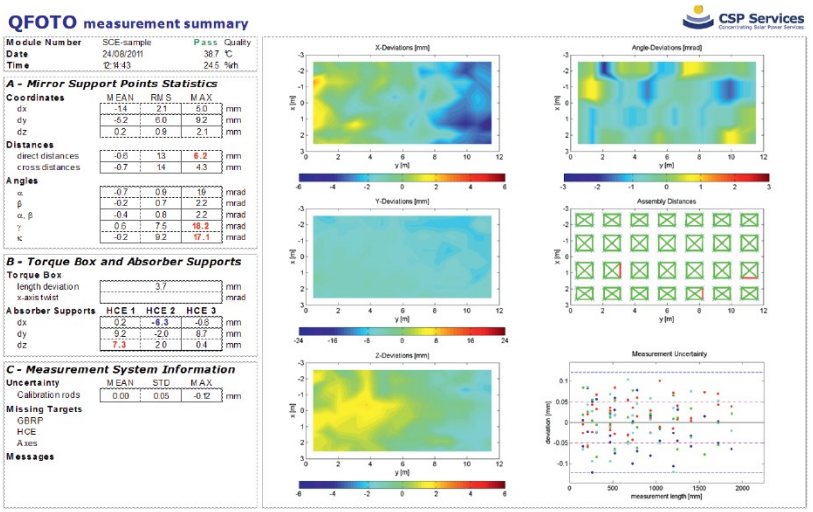
optical

QFoto: Photogrammetry Setup for Collector Structures



QFoto: Automated System for *Collector Structures*

Moving Camera



QFoto-Module Quality Report

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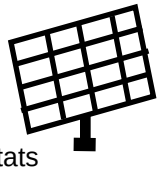 Heliostats	SAPHIR Deflectometry, + Intercept Simulation Photogrammetry, Inclinometer	Photogrammetry, QFoto Laser Tracker	
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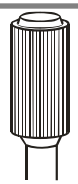
 Central Receiver			

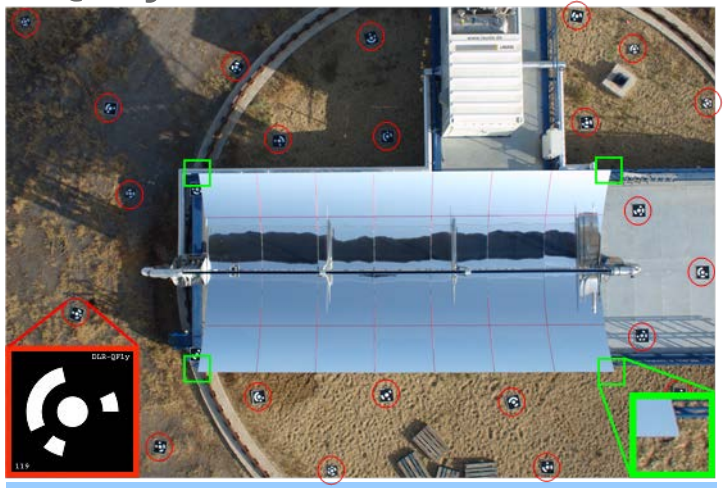
2. Qualification of Concentrators

optical

Collector Field Shape Measurement: QFly

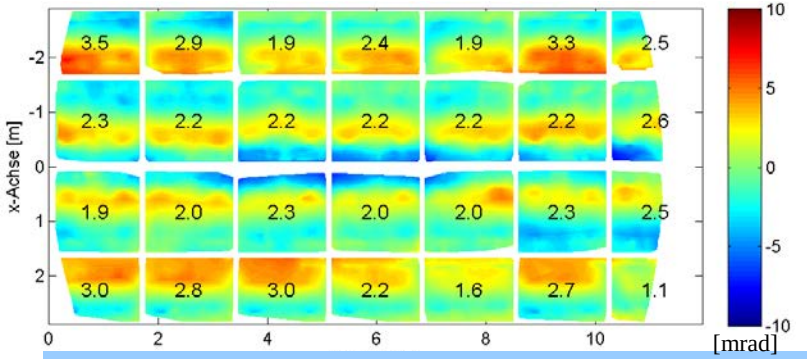
a) Airborne camera vehicle during a test flight at KONTAS test facility (PSA)

b) Automatic creation of flight routes (DISS, PSA)



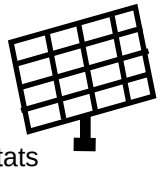
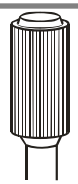
c) Photogrammetric determination of camera and collector position

- System successfully **validated** for single module (against TARMES and Photogrammetrie)
- **Measurement uncertainty**:
  local slope deviation.: 0.6 – 1.1 mrad
  RMS whole module: ca. 0.1 mrad
- Up scaling to complete **solar fields**



d) Slope deviation measured by QFly for KONTAS collector

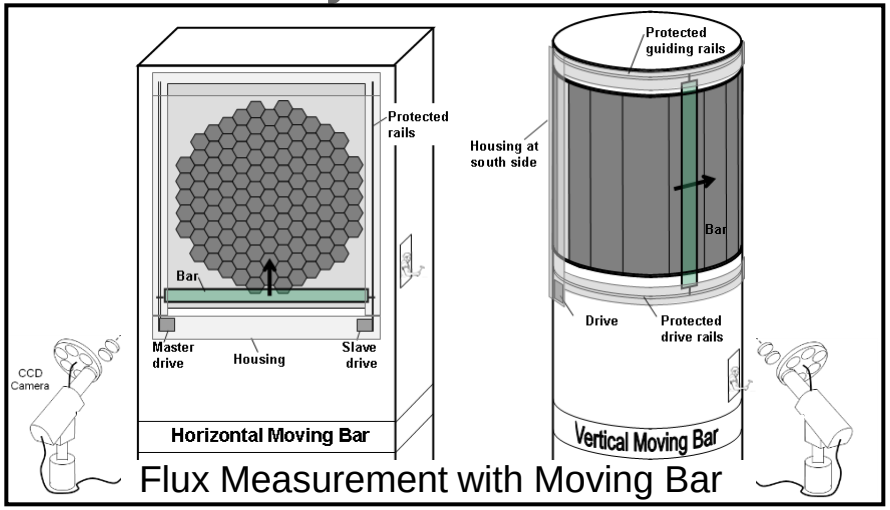
Qualification in Different Phases

Phases Objects	R&D Phase Prototypes	Production Phase Mass Product	O&M Phase Commissioned Plant
Concentrator  Parabolic Trough Coll.	TARMES Deflectometry + Intercept Simulation Photogrammetry Inclinometer, V-Shot	QDec-M Deflectometry + Intercept Simulation QFoto Photogrammetry, Laser-Tracker	QFly Deflectometry, + Intercept Simulation Flux Density Simulation
 Heliostats	SAPHIR Deflectometry, + Intercept Simulation Photogrammetry, Inclinometer	Photogrammetry, QFoto Laser Tracker	SAPHIR Deflectometry Flux Density Simulation Flux Density Measurement
Receiver  Parabolic Trough Receiver			
 Central Receiver			

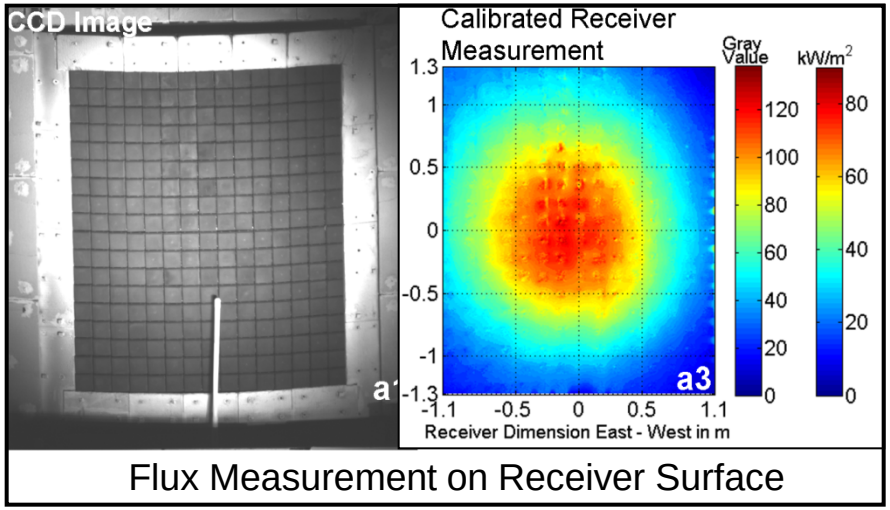
2. Qualification of Concentrators / Receivers

optical

Flux Density Measurement

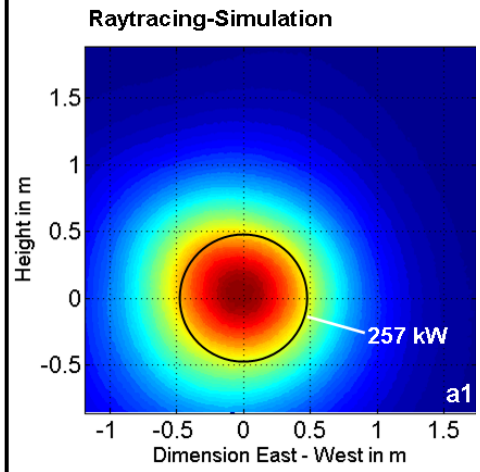


Flux Measurement with Moving Bar



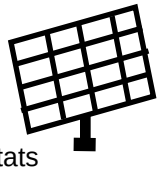
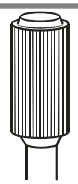
Flux Measurement on Receiver Surface

Heliostat Beam Characterization by Flux Measurement
- Canting
- Tracking Errors



Flux Density by Raytracing-Simulation

Qualification in Different Phases

Phases Objects	R&D Phase Prototypes	Production Phase Mass Product	O&M Phase Commissioned Plant
Concentrator  Parabolic Trough Coll.	TARMES Deflectometry + Intercept Simulation Photogrammetry Inclinometer, V-Shot	QDec-M Deflectometry + Intercept Simulation QFoto Photogrammetry, Laser-Tracker	QFly Deflectometry, + Intercept Simulation Flux Density Simulation
 Heliostats	SAPHIR Deflectometry, + Intercept Simulation Photogrammetry, Inclinometer	Photogrammetry, QFoto Laser Tracker	SAPHIR Deflectometry Flux Density Simulation Flux Density Measurement
Receiver  Parabolic Trough Receiver	ThermoRec, KONTAS, ElliRec, Mechanical Prop. OptiRec,		
 Central Receiver			

3. Qualification of Receivers

thermal

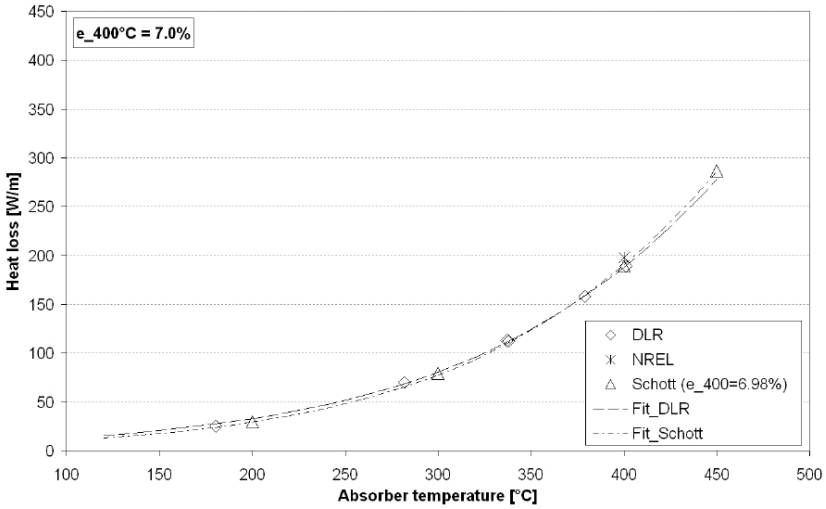
Receiver Qualification - ThermoRec

Measurements:

- Standardized Component Qualification
- Laboratory Measurement of Thermal Losses
- Principle: Electrical Heating = Heat Loss

Features:

- Internal Electric Heating
- End Heaters for Homogeneous Temperature Profile
- Temperature Measurement of
  - Absorber inside
  - Glass Envelope
  - End Caps Surface
- Calculation of Axial End Losses (~3%) and Correction of Power



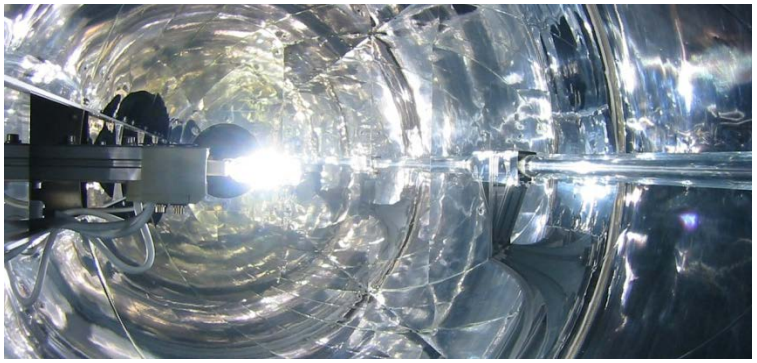
3. Qualification of Receivers

optical

Receiver Qualification - ElliRec

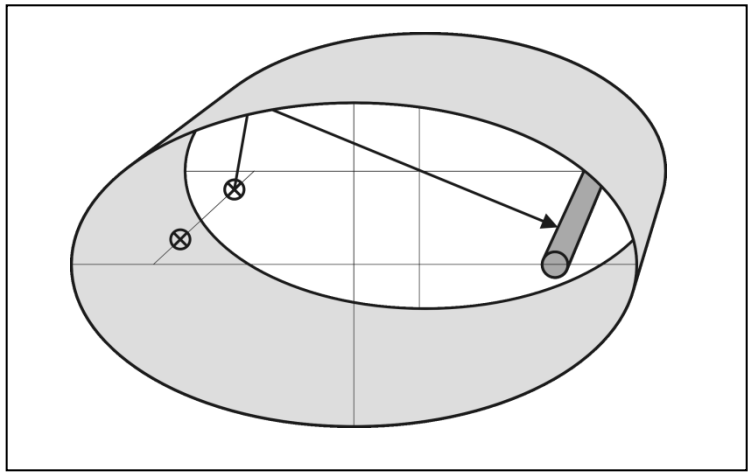
Measurements:

- Standardized Component Qualification for *Comparative Measurements*
- Laboratory Measurement of Optical Performance



Measurement Principle:

- Heating by Metal-Halide Lamps and Elliptical Concentrator
- No Thermal Losses, as Ambient Temperature
- Measuring Flow Rate of Water
- Measuring Temperature Increase (ΔT ~ 7 K)
  → Absorbed Power
- Exact Lamp Power unknown, but constant



→ *Comparative Measurements* to one Virtual 70-mm Master Receiver

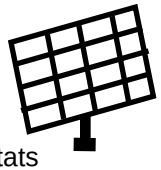
OptiRec: 2nd generation test bench for Optical Receiver

Method:
- similar to ElliRec

Goals:
- improve long term stability of optics and reproducibility
- facilitate replication → standardization
- improved handling
- shorter measurement time
- smaller dimensions

Status:
- operational since early 2013
- high reproducibility of the measurement of ~ ± 0.2 (1σ) shown
- compatibility with ElliRec shown

Qualification in Different Phases

Phases Objects		R&D Phase Prototypes	Production Phase Mass Product	O&M Phase Commissioned Plant
Concentrator	 Parabolic Trough Coll.	TARMES Deflectometry + Intercept Simulation Photogrammetry Inclinometer, V-Shot	QDec-M Deflectometry + Intercept Simulation QFoto Photogrammetry, Laser-Tracker	QFly Deflectometry, + Intercept Simulation Flux Density Simulation
	 Heliostats	SAPHIR Deflectometry, + Intercept Simulation Photogrammetry, Inclinometer	Photogrammetry, QFoto Laser Tracker	SAPHIR Deflectometry Flux Density Simulation Flux Density Measurement
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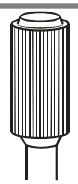
	 Central Receiver			

3. Qualification of Concentrators & Receivers optical & thermal

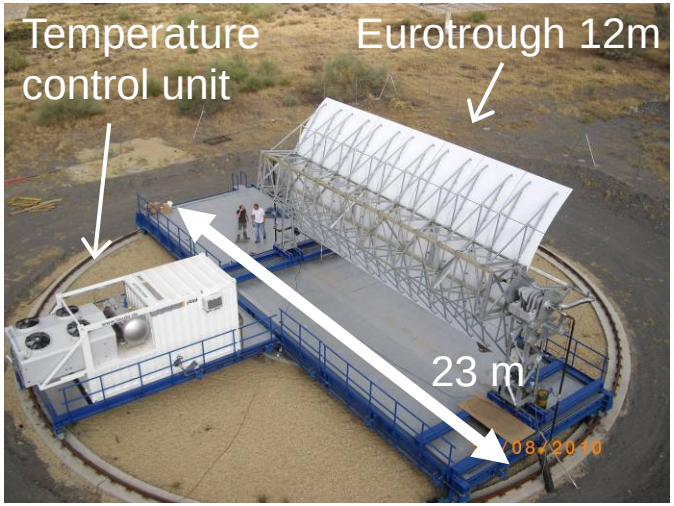
KONTAS Test Bench at PSA

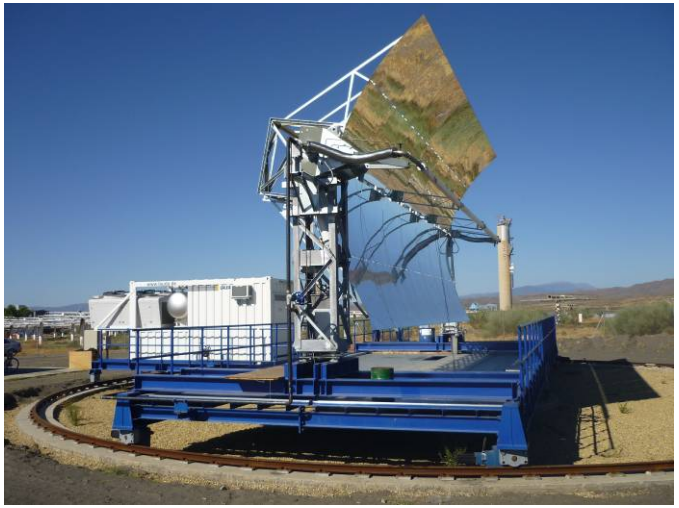
Measurements:

- Standardized Component Qualification
- On-Sun Measurement of Optical and Thermal Efficiency
- Component Performance

Features:

- Rotative test-platform
- Max. Collector Length: 20 m
- Active Temperature Control
- Heat Transfer Fluid: Syltherm 800
- Operation Temperature: ≤ 400 ° C
- Mass Flow: <6 kg/s
- High Precision Meteo Station
- Redundant Calibrated PT-100





Qualification in Different Phases

Phases Objects		R&D Phase Prototypes	Production Phase Mass Product	O&M Phase Commissioned Plant
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	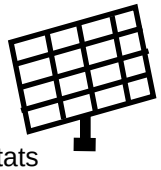 Heliostats	SAPHIR Deflectometry, + Intercept Simulation Photogrammetry, Inclinometer	Photogrammetry, QFoto Laser Tracker	SAPHIR Deflectometry Flux Density Simulation Flux Density Measurement
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	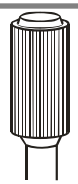 Central Receiver	Receiver Efficiency Meas.	Several manufacturing specific quality control measures	

Qualification in Different Phases

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	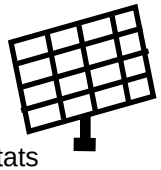 Heliostats	SAPHIR Deflectometry, + Intercept Simulation Photogrammetry, Inclinometer	Photogrammetry, QFoto Laser Tracker	SAPHIR Deflectometry Flux Density Simulation Flux Density Measurement
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	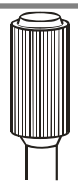 Central Receiver	Receiver Efficiency Meas.	Several manufacturing specific quality control measures	Receiver Efficiency Meas.

Qualification in Different Phases

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	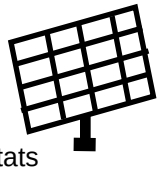 Heliostats	SAPHIR Deflectometry, + Intercept Simulation Photogrammetry, Inclinometer	Photogrammetry, QFoto Laser Tracker	SAPHIR Deflectometry Flux Density Simulation Flux Density Measurement
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	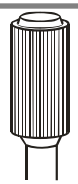 Central Receiver	Receiver Efficiency Meas.	Several manufacturing specific quality control measures	Receiver Efficiency Meas.

Conclusion

- Optical quality of components and their alignment are critical for the commercial success of CSP plants

- High quality measurement systems on component and subsystem level exist and are partly transferred to industry

- Measurement systems together with Ray tracing and Finite Element Tools improve the understanding of the system and allow for optimization

- We feed our experience on optical and thermal performance measurements into standardization initiatives

- In situ performance and degradation measurements is one important subject for further development

Final Quality Inspection Procedure …

DLR